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Project C3: Dynamics of Sports Stadiums

Development of models for determination of the dynamic load from spectator movement

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In the design of sports stadiums the dynamic effects from spectator movement constitutes an important part. In the present project the main focus has been on the development of spectator load models that give a realistic representation of the vertical force exerted by the individual spectator on the structure, when performing repetitive motion. Analytical expressions of force amplitude spectra for both deterministic and stochastic pulse trains have been found for a variety of different impulse shapes. Experimental investigations have been performed for vertical motions at different motion frequencies in order to determine the relevant motion parameters, the experimental load spectra, the influence of the structural eigenfrequency and the structural stiffness. A theoretical, a computational and two experimental investigations have been performed. These investigations show that it is possible to use impulse based models for assessment of the vertical force exerted by repetitive vertical human motion.

Development of analytical load models

The theoretical research reported in [1] concerns the investigation of the mechanics of repetitive human motion and involves an analysis of the influence of different impulse shapes, i.e. different force-time functions. The Fourier transforms of pulse trains of the impulse functions are used to find deterministic and stochastic force amplitude spectra. In the theoretical work it has been assumed that the structure is infinitely stiff. The validity of this assumption is sought in the second experimental investigation, [2]. The first experimental investigation, [3], concerns the determination of the main parameters needed to describe the loads for motion on a very stiff structure.

Introducing the impulse starting time within each mean period or the period between impulses as a stochastic variable it has been possible to develop analytical load models in the frequency domain, which include the variance of the impulse starting times or the variance of the pulse periods. These models can be expanded to crowd loads using a corresponding crowd variance. (This can be done by summing up multiple impulses within a period).

Computational investigation of stochastic repetitive load

The analytical models for the spectral distribution of repetitive vertical human loading, mainly jumping, have been validated through the use of simulated discrete time series of the load. The computational investigation is described in [4]. The simulation is performed on the basis of halfsine impulse shapes and experimentally determined mean values and standard deviations of the pulse period, the pulse starting time and the contact durations. The simulations show that the developed analytical expressions for the spectral load distribution are adequate.

Experimental investigation of repetitive vertical human loading

The first experimental investigations reported in [2] involves **one** person performing repetitive vertical motion on a very stiff square measuring platform 0.80 m x 0.80 m. Time series of the loads on the platform and the motion of the waist are recorded. The experiments are performed at motion frequencies varying from 0.5 Hz to 3.2 Hz using a metronome. Two test series with two different test persons were performed. The motions performed at each frequency include movements, where the amplitude of the vertical motion is as large as possible, for example by repetitive jumping from a position with bent knees. Mechanical and experimental analysis shows that the maximum movement is obtained for low frequencies. At each frequency the person is asked to perform the following motions:

a) high jumping with the largest possible movement (bending of knees)
b) high jumping with the smallest possible contact duration (on toes)
c) jumping with the largest possible contact duration (stamping)
d) normal jumping
e) large amplitude vertical motion with continuous contact (knee bends)

These motion types are believed to be sufficient for the purpose of defining spectral force envelopes to be used in the ultimate state and the serviceability state. The influence of the number of people is not considered in the experimental work, but the mechanical investigations have opened a path for further investigations.

The experimental investigations show that it should be possible to use the developed impulse based load models for repetitive vertical human loading. The experiments have been illustrated by direct plots and force amplitude spectra.

Experimental investigation of the structural influence

The second experimental investigation reported in [3] was performed in order to investigate the influence of the structural stiffness (the structural displacement amplitude) and eigenfrequency on the repetitive vertical human motion and the related loads exerted by the human being.

The "structure" used in the experimental setup consists of a 1.6 m x 1.6 m square steel frame supported at the corners on flexible springs. By adding mass to the frame and choosing springs of varying stiffness it is possible to emulate structures of different stiffness and eigenfrequency. On top of the steel frame the small square measuring platform is mounted and a test person is asked to jump at given frequencies or to induce resonance by fast knee bends (with continuous contact). Both normalized load amplitude spectra and normalized structural displacement response amplitude spectra have been calculated for all experiments.

Nine different experimental structural setups have been used. The experimental structural setups have eigenfrequencies of about 3 Hz, 4 Hz or 6 Hz. For each eigenfrequency three different stiffnesses have been chosen. Thus enabling the experimental investigation of the influence of the displacement amplitude and the eigenfrequency on the load spectrum and human behavior.

The experimental investigations performed show that the impulse based load models for repetitive vertical human loading developed in [1] can be used and that the influence of the deflection amplitudes and the motion frequency is limited to a small increase in the standard deviations of the main motion parameters as shown in the previous section. However the influence is not systematic and the number of experiments have been limited. By comparing the variation of the motion parameters to the variations found for jumping on a stiff structure it is found that the contact duration ratio has the same variation with frequency and that the standard deviations of the periodic starting times are in the same order of magnitude, but with greater non systematic deviations between the individual experiments.

The experimentally found normalized force amplitude spectra for jumping show that load models based on repetitive impulses give reasonable representations of the load spectra for motions at different frequencies and with different contact duration ratios. The normalized displacement amplitude spectra show that simple dynamic response analysis can be used to find the structural response.

Main results

The main results of the project is that analytical expressions for deterministic and stochastic load spectra for repetitive impulses have been developed and that these can be used for prediction of the load spectra for repetitive vertical human motion. A number of important parameters related to the deterministic and stochastic description of repetitive vertical human motion have been determined experimentally. The structural influence on these parameters have also been investigated experimentally. For the development of a more complete load model for spectator movement research into the spatial distribution of loads from many spectators over larger areas and the participation degree will have to be performed. The influence of heel impact on the high frequency domain is needed if the models are to be applied for analysis of the service state. One method has been proposed for the inclusion of heel impact.

References

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